Laser melt injection of ceramic particles in metals

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Summary

The field 'surface engineering' has been greatly driven by the realization that the surface is usually the most important part of an engineering component. Structural components fail by high cycle fatigue, corrosion, friction and wear, i.e. failure is affected and initiated by the surface conditions. To enhance surface performances, an appropriate approach is to modify the surface layer of a base material. Indeed there exists an almost bewildering set of surface treatments but the choice has to be such that the surface treatment does not impair too much the properties of the substrate material, that is to say it should not be reduce too much the load carrying capabilities of the bulk. The objective of this thesis is to study the possibilities of the Laser Melt Injection (LMI) process to enhance the surface of light-weighted metals by adding hard ceramic particles in the top layer, with the aim to enhance the wear resistance and to increase the hardness.

In the LMI process, a laser beam locally melts the top layer of a metal workpiece. Meanwhile, ceramic particles are injected in the melt and are trapped when the melt pool rapidly resolidifies after the laser beam has passed. The result is that in top layer a Metal-Matrix Composite (MMC) is created, without affecting the bulk of the metal workpiece. The properties of the MMC coatings depend strongly on the bonding between the ceramic particles and the metal matrix. However, the wetting of liquid metals on ceramic materials is usually poor. Therefore, to obtain a good bonding, materials are chosen in such a way that a chemical reaction between the particle and matrix occurs. This reaction leads to the formation of a reaction zone between the particle and matrix, which is responsible for the bond strength.

The LMI process and the resulted microstructures of two material systems, i.e. SiC particles in Al and WC particles in Ti-6Al-4V, are examined in this work. In addition, the microstructural response on loading of both systems is studied. The microstructure is analyzed in detail by advanced microscopy techniques such as Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), and Orientation Imaging Microscopy (OIM).

Injection of SiC particles in Al

LMI of SiC particles in Al is a challenging but complex system. The processing parameters, i.e. power density of the laser beam, velocity of the laser beam and geometry of the injection system, should be carefully tuned because the parameter window, for which processing a SiC_P/Al MMC is successful, is rather small. The difficulties are due to a large difference between the laser light absorptivities of SiC and Al, as well as the presence of an oxide skin on the Al melt. The former limits the laser power density that can be used because a high power density, needed to melt Al, will damage the SiC particles, having a much higher absorptivity. The second problem, i.e. the oxide skin on the Al melt, hampers the penetration of the SiC particles because the kinetic energy of the particles is lower than the energy needed to break the oxide skin on the surface. At a melt pool temperature of about 850 °C, the oxide skin starts to dissolve resulting in the formation of unoxidized Al islands at the melt pool surface. At about 1100 °C the oxide skin fully disappears. To analyze the influence of this oxide layer on the final injection depth of the particles, a physical model is developed. This model consists of two parts. In the first part the energy loss of a penetrating particle is calculated (derived from the change in energy estimated by the surface tensions). In the second part, the velocity and depth of a moving particle in liquid Al are calculated. Injection conditions are predicted and experimentally confirmed when about 50% or less of the surface is oxidized. The final injection depth is mainly controlled by the fraction of oxidized surface, i.e. the temperature of the melt pool. Therefore, in this temperature range, a small temperature change has a significant effect on the injection depth.

Preheating the substrate to above 300 °C during laser treatment is an effective method to dissolve enough oxide and to create appropriate injection conditions. In this way the laser power can be limited to avoid overheating of the SiC particles that pass through the laser beam during the injection process.

The resulting MMC layers have a particle volume fraction of about 35%, and are free of holes and cracks. During the laser process, when the surface layer of the SiC particles react with liquid Al, Al_4C_3 and Si are formed. Al_4C_3 appeared in platelet shape both in the melt pool matrix and at the SiC/Al interface, i.e. as a reaction layer. Si is found in Al-Si eutectic regions between the Al_4C_3 plates. It is observed that the Al_4C_3 plates in the reaction layer prefer to grow with the basal planes parallel to the basal planes of the SiC particle, pointing at an interaction between SiC and Al_4C_3.

Injection of WC particles in Ti-6Al-4V

It is demonstrated that LMI is a suitable technique to form a WC_p/Ti-6Al-4V MMC layer in the top layer of Ti-6Al-4V. The relative ease to create a melt pool in the Ti-alloy allows a certain variation of the laser track dimensions and volume fraction of the WC particles. It is also possible to coat a larger surface area by producing multiple adjacent tracks with an overlap of about 10%.

During the laser process, a number of phases formed: TiC, W and W_2C. In the top of the resolidified melt pool high amounts of TiC and W dendrites are present. This is due to the reaction between liquid Ti and liquid or dissolved WC that is dripped off the heated WC particles during penetration in the melt pool. The liquid or dissolved WC that is remained at the particle surface during penetration reacts with the Ti melt to form a W_2C and TiC reaction layer around the WC particles. W_2C tends to grow in the [0001] direction. When the surface of the WC particle is close to the (0001) basal plane, W_2C can minimize the atomic misfit at the WC/W_2C interface by growing according an orientation relation (i.e. crystallographic orientation of the W_2C crystal is correlated to the crystallographic orientation of the WC crystal), and simultaneously obey the preferred [0001] growth direction. In the case of an orientation relation between WC and W_2C, also an orientation relation between W_2C and TiC exits. The misfits between W_2C and TiC are minimized if the (111) planes of TiC fit on top of the (0001) planes of W_2C. The presence of orientation relations between the reaction layers indicates that indeed there is interaction between the layers, affecting the bonding between particles and matrix in a positive sense. Therefore, it is preferred to inject WC particles that have a relatively large amount of (0001) surfaces. This is, for example, the case for WC powder that is produced by cleavage.

Microstructural response on loading

To obtain information on the bond strength between the particles and matrix the MMC layers are exposed to tensile loads. *In-situ* tensile tests in a scanning electron microscope are performed to observe the crack nucleation and propagation process. In this way, the strongest and weakest microstructural features can be pinned down. This information may be used to optimize the coatings.

The tensile strength of the SiC_p/Al MMC coatings produced by the laser melt injection process is higher than the tensile strength of the untreated material. This increase in strength is mainly due the change in microstructure by the rapid solidification of Al during laser processing and residual stresses caused by the laser processing rather than due to the injected SiC particles. The Al_4C_3/Al interfaces of the Al_4C_3 plates that are present between the particles in the melt pool matrix are the weakest links in the produced MMC coatings. These interfaces easily decohere, making them favorable sites for crack nucleation and propagation along the plates that are randomly distributed in the matrix. Under a tensile load cleavage of the SiC particles is the second most important crack nucleation and propagation mechanism. It is striking to see that decohesion of the SiC/Al interface does not frequently occur. From this it is concluded that the Al_4C_3 plates in the reaction zone form a good bonding between particle and matrix. However, due to decohesion between the Al matrix and the plates in the matrix, the existence of Al_4C_3 plates in the Al matrix should be minimized.

The tensile strength and ductility of the WC_p/Ti-6Al-4V MMC coating produced by the laser melt injection process decrease with respect to the substrate material properties. The main reasons are the two predominant failure initiation mechanisms: intergranular brittle fracture inside the granular WC particles and decohesion along the WC/W_2C interface. During loading in tension, pre-cracks are formed at low external stress or even induced by the internal stresses that are introduced during the laser process. The failure proceeds by cleavage of the TiC dendrites that are present in high amounts in the melt pool matrix. To improve the tensile properties, powder that consists of single WC grains can be used during the injection process to avoid intergranular fracture. In addition, the particles should be injected behind the laser beam. This will minimize the presence of brittle TiC in the melt pool matrix, which will improve the performance of the coating.

Conclusions

The laser melt injection process is a suitable technique to create a MMC layers on metal substrates. The formation of reaction layers between the particles and the matrix may have a positive contribution on the bond strength between the particles and the matrix. However, the amount of reaction products in the matrix of the coatings should be minimized to improve the properties of the MMC layers.